EurJOC European Journal of Organic Chemistry

FULL PAPER

DOI: 10.1002/ejoc.201200989

Synthesis of Pyrimidine-Modified NHC Ruthenium-Alkylidene Catalysts and Their Application in RCM, CM, EM and ROMP Reactions

Guang-Long Wu,[a,b] Sheng-Li Cao,*[a] Jian Chen,*[b] and Zili Chen*[c]

Keywords: Synthetic methods / Homogeneous catalysis / Ruthenium / Nitrogen heterocycles / Metathesis

A new type of N-heterocyclic carbene bearing ruthenium olefin metathesis catalyst was prepared through the incorporation of a chelated pyrimidinyl methylene subunit, in which electron-rich substituents were attached to stabilize the ruthenium complexes. These catalysts were successfully used in various types of olefin metathesis reactions, including ring-closing metathesis (RCM), cross-metathesis (CM), enyne metathesis (EM), and ring-opening metathesis polymerization (ROMP) reactions. The results therein showed that the presence of an electron-deficient pyrimidine structure greatly enhanced the new NHC ruthenium complexes' catalytic activities.

Introduction

The development of powerful air-stable catalysts has made olefin metathesis an indispensable tool in a variety of fields including organic synthesis, materials science, and biochemistry.[1] Among multiple metal-based complexes enabling olefin metathesis transformations, ruthenium-benzylidene pre-catalysts bearing N-heterocyclic carbene (NHC) ligands exhibited extraordinary activity and stability.[2] Mechanistic studies upon the NHC-complexed ruthenium-benzylidene pre-catalysts **1** (Figure 1) revealed that a low ratio of phosphane reassociation to substrate binding was necessary for its high activity.[3] In 2000, phosphane-free NHC complex **2** (Grubbs-Hoveyda catalyst) was developed, in which, a chelating benzylidene structure (Figure 1) provided superior stability.[4] However, this catalyst initiates more slowly than highly-active catalyst **1** as a result of steric (large isopropoxy group) and electronic factors (*i*PrO to ruthenium electron donation). Based on these findings, significant effort has been devoted to develop stable and active new catalysts through modifying the benzylidene unit or chelated isopropoxy fragment of complex **2**.[5–7]

In order to enhance the leaving ability of the benzylidene ligand, complex **3** was reported by Blechert group, which increased the neighboring steric bulk of the isopropoxy group (Figure 1).[6] Almost at the same time, the Grela group developed complex **4** through a different approach, in which an electron-withdrawing nitro group was introduced to reduce the benzylidene unit's chelating ability (Figure 1), thus facilitating formation of the catalytically active 14-electron Ru carbene species, and suppressing repeated reassociation to the metal center.[7] We herein want

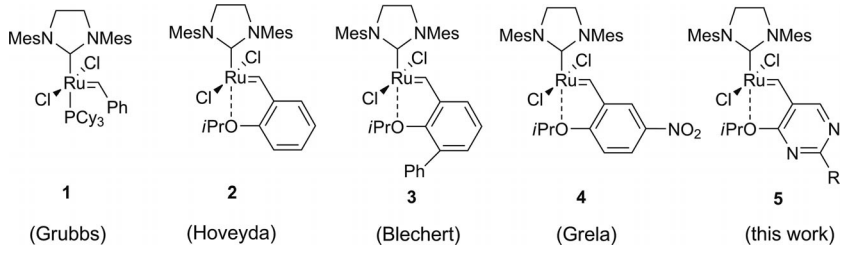


Figure 1. Ruthenium metathesis catalysts.

to report a new variant of complex **2** in which we replace the phenyl group with an electron-deficient pyrimidine unit (complex **5**, Figure 1). We envisioned that the presence of the electron-deficient pyrimidine group would also improve the ruthenium complex's reactivity. Additionally, the ease of introducing functionality between the two nitrogen atoms in complex **5** might provide new possibilities in the design of new types of ruthenium olefin-metathesis cata-

[a] Department of Chemistry, Capital Normal University, Beijing 100048, P. R. China
E-mail: slcao@cnu.edu.cn
Homepage: http://202.204.208.66/hxx/index.php?q=node/207
[b] Bioduro (Beijing) Co. Ltd., Beijing 102206, P. R. China
[c] Department of Chemistry, Renmin University of China, Beijing 100872, P. R. China
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/ejoc.201200989.

lysts. In previous reports, a heterocyclic pyridine group has been used as a complexing ligand in phosphane-free ruthenium catalysts.[8] However, this is the first report, to the best of our knowledge, of incorporating a chelating heterocyclic unit into the alkylidene unit in NHC-ruthenium complexes (Figure 1).

Results and Discussion

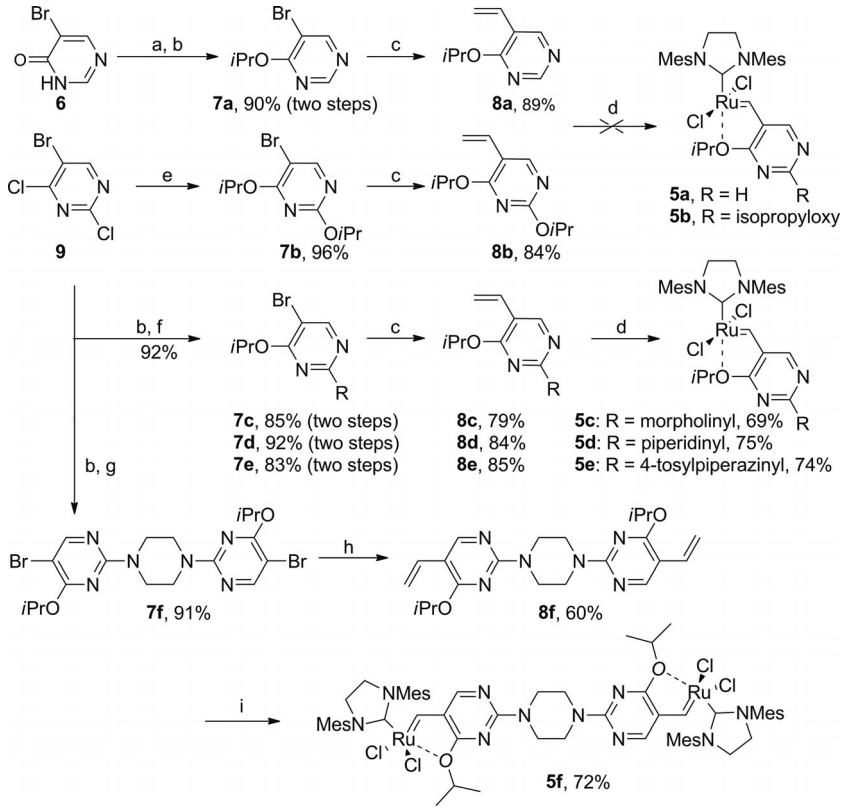
A variety of vinylpyrimidine derivatives **8a**–**f** have been designed for the preparation of the pyrimidine-modified NHC ruthenium-alkylidene complexes **5**. Our synthetic routes started from commercially available 5-bromopyrimidin-4(3*H*)-one (**6**) and 5-bromo-2,4-dichloropyrimidine (**9**). As shown in Scheme 1, treating compound **6** with $POCl_3$ under reflux conditions gave its 4-chloro analogue, which then reacted with *i*PrONa in THF at low temperature to provide **7a** in 90% yield (2 steps). Stille coupling of **7a** with tributylvinyltin by using palladium catalysis in a mixture of dioxane/H_2O afforded 4-isopropoxy-5-vinylpyrimidine (**8a**) in 89% yield. However, the reaction of **8a** with complex **1** in CH_2Cl_2 gave no desired pyrimidine-modified NHC ruthenium-alkylidene **5a**, possibly owing to its instability.[9,10]

We then turned to synthesize 2,4-diisopropoxy-5-vinylpyrimidine (**8b**). Its bromo precursor **7b** was prepared from reaction of compound **9** with *i*PrONa (2 equiv.). Stille coupling of **7b** provided **8b** in 84% yield. But the effort to synthesize **5b** from **8b** was fruitless.

We considered that a more electron-rich pyrimidinylmethylene subunit would stabilize the ruthenium complex. Therefore, electron-rich amino substituents bearing vinylpyrimidine derivatives **8c**–**e** were designed. Treating **9** with *i*PrONa (1 mol equiv.), followed by piperidine attachment readily afforded 4-isopropoxy-2-piperidiny-5-vinylpyrimidine (**7c**) in 85% yield. Compound **8c**, synthesized from **7c** through a Stille coupling, reacted with complex **1** in CH_2Cl_2 by using CuCl as a scavenger, giving pyrimidine-modified NHC ruthenium-alkylidene complex **5c** in 75% yield. Similarly, complexes **5d** and **5e** were also prepared in moderate to good yields through four step reactions (Scheme 1).

A symmetric dimeric pyrimidine-modified NHC ruthenium-alkylidene **5f** was then synthesized by using piperazine as the bridge. Successive treatment of **9** with *i*PrONa (1 mol equiv.) and piperazine (0.5 mol equiv.) gave **7f** in 91% yield. Subsequent vinyl coupling and complexation with ruthenium afforded dimeric complex **5f** in 72% yield (Scheme 1).

The structures of complexes **5c**–**f** were all characterized from their ^1H NMR and ^{13}C NMR spectroscopic data and element analyses.



Scheme 1. Preparation of catalysts **5c**–**f**. *Reagents and conditions:* (a) $POCl_3$, reflux, 2 h. (b) THF, *i*PrONa (1.0 equiv.), –20 °C to r.t. (c) CH_2=CHS*n*Bu_3 (1.5 equiv.), $Pd(dppf)Cl_2$ (5 mol-% equiv.), dioxane/H_2O (5:1), 60 °C, overnight. (d) **1** (1.05 equiv.), CuCl (3.0 equiv.), CH_2Cl_2, reflux, 1 h. (e) THF, *i*PrONa (2.0 equiv.), –20 °C to r.t.. (f) RH (3.0 equiv.), 60 °C, 6 h. (g) Piperazine (0.5 equiv.), 60 °C, 6 h. (h) CH_2=CHS*n*Bu_3 (3 equiv.), $Pd(dppf)Cl_2$ (0.1 equiv.), dioxane, H_2O, 60 °C, overnight. (i) **1** (2.1 equiv.), CuCl (6.0 equiv.), CH_2Cl_2, reflux, 1 h.

Having these new complexes in hand, we started to explore their relative catalytic activities. RCM reaction of diallyltosylamide (**10a**) was chosen as the model system for our initial investigation. All representative results are collected in Figure 2. As shown in Figure 2, the difference between the catalytic activities of complexes **5c**, **5e** and **5f** were minimal. Complex **5d** exhibited the lowest activity, whereas **5c** and **5f** showed better activities. Although the activities of **5c**–**f** were lower than that of catalyst **4**, complexes **5c**–**f** were dramatically more active than parent Hoveyda catalyst **2**. Interestingly, bis-ruthenium complex **5f** (0.5 mol-% of **5f**) initializes the reaction visibly faster than mono-ruthenium **5c**, **5d** and **5e** (1.0 mol-%; Figure 2).

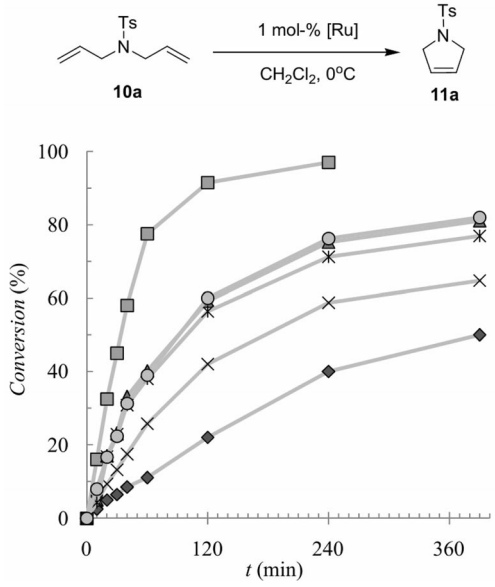
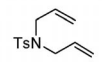
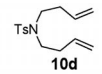
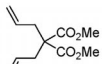
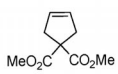
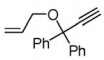


Figure 2. Relative rates of diene **10a**'s RCM reaction with catalysts **2**, **5c**, **5d** and **5e** (1 mol-%), and **5f** (0.5 mol-%). (diamond: catalyst **2**, square: catalyst **4**, triangle: catalyst **5c**, cross: **5d**, asterisk: **5e**, circle: **5f**).

In order to further explore the complexes' catalytic activities, a series of low-catalyst-loading experiments were performed. RCM reactions of diene substrates **10a**, **10d**, **10f** and **10g** were tested, in which four carbo- or heterocyclic molecules **11** were obtained. As shown in Table 1, three levels of catalyst loading (1 mol-%, 0.5 mol-% and 0.2 mol-% based on ruthenium metal concentration) were tested. When 1 mol-% of catalyst was utilized, all reactions were complete in 1 h, giving the desired product in quantitative yields (Table 1, Entries 1, 4, 7 and 10). When 0.5 mol-% of catalyst was added, high reaction yields were obtained in 2 h (Table 1, Entries 2, 5, 8 and 11). However, when 0.2 mol-% of catalyst was added, the reaction yields decreased significantly, even after a longer reaction time (Table 1, Entries 3, 6, 9 and 12).

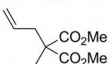
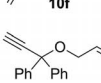
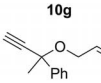
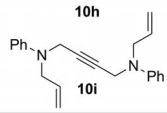
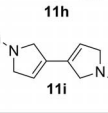
Encouraged by previous results, metathesis reactions of various diene or enyne substrates were then examined and representative results are shown in Table 2. As illustrated in Table 2, complexes **5c**–**e** served as effective catalysts for the formation of di- and trisubstituted five-, six-, and seven-membered cyclic molecules from TsN- or malonate-bridged

Table 1. Low-catalyst-loading experiment.[a,b]

	Substrate	Product	Catalyst loading	Yield [%][c] 5c	5d	5e	5f
1[e]	 10a	 11a	1.0%	99 (98[d])	99	99	99
2			0.5%	99	99	98	99
3			0.2%	41	50	31	52
4	 10d	 11d	1.0%	99	99 (95[d])	99	99
5			0.5%	99	99	99	99
6			0.2%	64	59	61	72
7	 10f	 11f	1.0%	99	99	99 (93[d])	99
8			0.5%	99	98	95	99
9			0.2%	44	50	31	26
10	 10g	 11g	1.0%	99	99	99	99 (99[d])
11			0.5%	99	99	99	99
12			0.2%	73	60	61	75

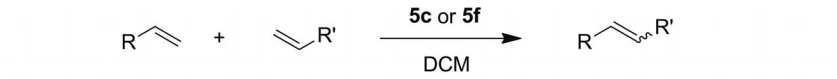
[a] Unless noted, all reactions were performed in CH_2Cl_2 at 25 °C and the catalyst loading ranged from 1.0% to 0.2% (based on ruthenium metal concentration). [b] Reaction time: 1 h for 1.0% catalyst loading, 2 h for 0.5% and 4 h for 0.2%. [c] Yields were determined by GC. [d] Isolated yields. [e] The percentage recovery of catalysts **5c**–**f**: **5c**, 74%; **5d**, 68%; **5e**, 71%; **5f**, 27%.

Table 2. Catalysts **5c**, **5d**, **5e** and **5f** in RCM and EM reactions.[a]

Entry	Substrate	Catalyst ([mol-%])	Conditions	Product	Yield [%][b]
1	 10a	**5c** 0.50 **5d** 0.50 **5e** 0.50 **5f** 0.25	25 °C 2 h 25 °C 2 h 25 °C 2 h 25 °C 2 h	 11a	>99 >99 >98 >99
2	 10b	**5c** 0.50 **5d** 0.50 **5e** 0.50 **5f** 0.25	25 °C 2 h 25 °C 2 h 25 °C 2 h 25 °C 2 h	 11b	95 >99 96 >98(97[c])
3	 10c	**5c** 0.50 **5d** 0.50 **5e** 0.50 **5f** 0.25	25 °C 2 h 25 °C 2 h 25 °C 2 h 25 °C 2 h	 11c	>99 >99 96 >99(97[c])
4	 10d	**5c** 0.50 **5d** 0.50 **5e** 0.50 **5f** 0.25	25 °C 2 h 25 °C 2 h 25 °C 2 h 25 °C 2 h	 11d	>99 >99 >99 >99
5[d]	 10e	**5c** 4.0 **5d** 4.0 **5e** 4.0 **5f** 2.0	80 °C 5 h 80 °C 5 h 80 °C 5 h 80 °C 5 h	 11e	68 62 63 70(70[c])
6	 10f	**5c** 0.50 **5d** 0.50 **5e** 0.50 **5f** 0.25	25 °C 2 h 25 °C 2 h 25 °C 2 h 25 °C 2 h	 11f	>99 >98 >95 >99
7	 10g	**5c** 0.50 **5d** 0.50 **5e** 0.50 **5f** 0.25	25 °C 2 h 25 °C 2 h 25 °C 2 h 25 °C 2 h	 11g	>99 >99 >99 >99
8	 10h	**5c** 0.50 **5d** 0.50 **5e** 0.50 **5f** 0.25	25 °C 2 h 25 °C 2 h 25 °C 2 h 25 °C 2 h	 11h	>99(95[c]) 97 96 >99
9[d]	 10i	**5c** 4.0 **5d** 4.0 **5e** 4.0 **5f** 2.0	80 °C 24 h 80 °C 24 h 80 °C 24 h 80 °C 24 h	 11i	85(80[c]) 78 75 87

[a] Unless noted, all reactions were performed in CH_2Cl_2 and the catalyst loading ranged from 4.0% to 0.25% (based on ruthenium metal concentration). [b] Yields were determined by GC. [c] Isolated yields. [d] Decomposition of complexes **5c**–**f** were observed at a high temperature.

Table 3. Catalysts **5c** and **5f** in intermolecular cross-metathesis reaction.[a]



Entry	Substrate	Catalyst (mol-%)	Product	Yield [%][b]
1	TBSO(CH2)4 + EtO2C (**12a** + **12b**, 2 equiv.)	**5c** 1.0 **5f** 0.5	TBSO(CH2)4CO2Et (**13a** (*E*/*Z* = 97/**3**))	92(89[c]) 90
2	TBSO(CH2)4 + NC (**12a** + **12c**, 2 equiv.)	**5c** 4.0 **5f** 1.0	TBSO(CH2)4CN (**13b** (*E*/*Z* =75/25))	70(65[c]) 57
3	TBSO(CH2)4 + OAc/OAc (**12a** + **12d**, 2 equiv.)	**5c** 1.0 **5f** 0.5	TBSO(CH2)4OAc (**13c** (*E*/*Z* = 93/7))	96(90[c]) 94(93[c])
4[d]	TBSO(CH2)4 + CO2Me/NHCbz (**12a** + **12e**, 2 equiv.)	**5c** 2.0 **5f** 0.5	CO2Me, NHCbz, TBSO(CH2)4 (**13d** (*E*/*Z* > 99/1))	86(62[c]) 85(65[c])
5[d]	TBSO(CH2)4 + Ph (**12a** + **12f,** 2 equiv.)	**5c** 2.0 **5f** 0.5	TBSO(CH2)4Ph (**13e** (*E*/*Z* > 99/1))	91(83[c]) 90(85[c])
6	Ph + OAc/OAc (**12f,** 2eq + **12d**, 2 equiv.)	**5c** 2.0 **5f** 0.5	Ph, OAc (**13f** (*E*/*Z* > 99/1))	87(84[c]) 92(92[c])

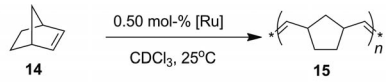
[a] Unless noted, all reactions were performed in CH_2Cl_2 for 2 h and the catalyst loading ranged from 1.0% to 4.0% (based on ruthenium metal concentration). [b] Yields were calculated from GC data. [c] Isolated yields. [d] Reaction time is 5 h.

substrates (Table 2, Entries 1–3, 5–7). The corresponding products were obtained in excellent yields at room temperature. In the reaction of diisobutenyl tosylamide substrate **10e**, tetrasubstituted olefin product **11e** was obtained in moderate yields in 5 h at an elevated temperature (Table 2, Entry 5). Enyne metathesis reaction of **10g** and **10h** afforded **11g** and **11h** in excellent yields at room temperature (Table 2, Entries 7 and 8). In addition, double-enyne metathesis reaction of dienyne substrate **10i** gave 3,3′-bipyrrole **11i** in moderate to good yields (Table 2, Entry 9). Relative to the results reported by the Grela group with catalyst **4**, complexes **5c**–**e** performed better in RCM reactions of **10g**.[7]

We then turned to investigate the intermolecular CM reactions of various substrates by using **5c** and **5f** as catalysts (Table 3). In CM reactions of **12a** (1 mol equiv.) with other alkenes (2 mol equiv.), including electron-deficient acrylate **12b**, electron-rich 2-butene-1,4-diacetate **12d**, allylamine substrate **12e** and styrene (**12f**), unsymmetrical disubstituted olefin products **13c**–**f** were obtained in good to excellent yields with a high degree of *E*-selectivity. Whereas in the reaction of **12a** with acrylonitrile **12c**, low to moderate yields and poor *E*/*Z* selectivity were observed, the CM reaction of **12f** with **12d**, *E*-configuration cinnamyl acetate (**13f**) was obtained in high yield.

We studied the catalytic activity of the new pyrimidine-bearing complexes in the ROMP of norbornene (**14**) by means of ^{1}H NMR spectroscopy monitoring (Table 4). It was found that ROMP reactions of **14** were complete in 30 min with catalysts **5c**–**f** with catalyst loadings as low as 0.5 mol-% (based on ruthenium concentration). The *cis*/*trans* ratio of polymer **15** was similar to Grubbs' result.[11,12]

Table 4. ROMP reactions of norbornene (**14**) with catalysts **5c**, **5d**, **5e** and **5f**.[a]



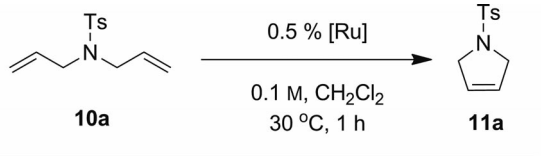
Catalyst ([mol-%])	Conditions	Conv. [%][b]	cis/trans ratio[b]
5c 0.50%	25°C 0.5 h	99	42/58
5d 0.50%	25°C 0.5 h	99	45/55
5e 0.50%	25°C 0.5 h	99	46/54
5f 0.25%	25°C 0.5 h	99	43/57

[a] Unless noted, all reactions were performed in CH_2Cl_2 with 0.5 mol-% catalyst (based on ruthenium metal concentration). [b] Yield and *cis*/*trans* ratio were determined by means of NMR spectroscopy.

The air stabilities of complexes **5c**–**f** were also tested. As shown in Table 5, the catalytic activities of **5c**–**f** remained

the same after 10 to 30 d air-storage, which indicates that complexes **5c**–**f** are quite stable.

Table 5. Stability study of the catalysts.[a]



Duration of storage (days)		0	10	30
Yield (%)[b]	**5c**	>99	98	98
	5d	>99	>99	98
	5e	>99	>99	>99
	5f	>99	98	98

[a] The catalysts were kept in air at room temperature. Unless noted, all reactions were performed in CH_2Cl_2 with 0.5 mol-% catalyst (based on ruthenium metal concentration). [b] Yields were determined by means of GC–MS analysis.

One of the unique properties of Hoveyda–Grubbs carbene **2** is that up to 95% of the catalyst can be recovered after the reaction.[4] We also attempted to recover the catalysts in the RCM reactions of **10a** (Table 1, Entry 1). It was found that **5c**, **5d**, **5e** and **5f** could be recovered with good to moderate efficiency (74–27%, Table 1 footnote), whereas high temperatures and longer reaction times (Table 2, Entries 5 and 9) lead to decomposition of **5c**–**f**.

Conclusions

In conclusion, a series of pyrimidine-modified NHC ruthenium-alkylidene complexes **5c**–**f** were prepared through the reaction of complex **1** with pyrimidine derivatives **8c**–**f**. Electron-rich 2-substituents, such as morpholinyl-, piperazinyl- and tosyl-piperazinyl groups, were attached to enhance these complexes' stabilities. All these complexes exhibited good air-stability and excellent catalytic activity[13] in metathesis reactions of dienes or enynes, and also in CM reactions and ROMP reactions. Considering its simple preparation, high activity and excellent stability, the preparation of new pyrimidine NHC ruthenium-alkylidene complexes could provide an attractive new approach to develop practical olefin metathesis catalysts.

Experimental Section

General: Unless otherwise noted, all reactions were performed under an inert atmosphere (N_2) with flame-dried glassware using standard techniques for manipulating air-sensitive compounds. The solvents were dried by distillation over the following drying agents: THF (Na/benzophenone), toluene (Na), *n*-pentane, *n*-hexane, CH_2Cl_2 (CaH_2), Et_2O ($LiAlH_4$), MeOH (Mg). All commercial reagents were used as received or purified by standard techniques where necessary. Column chromatography was performed using 200–300 mesh silica with the proper solvent system according to TLC analysis using $KMnO_4$ stain and UV light to visualize the reaction components. Unless otherwise noted, NMR spectra were recorded in $CDCl_3$, with proton and carbon resonances at 300 and 75 MHz, respectively, and are referenced to the residual solvent signal at δ = 7.26 ppm for ^1H and δ = 77.36 ppm for ^{13}C. Data for ^1H are reported as follows: chemical shift (δ ppm), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, sept = septet), coupling constant and integration. Data for ^{13}C NMR are reported in terms of chemical shift.

5-Bromo-4-isopropoxypyrimidine (7a): A solution of 5-bromopyrimidin-4(3*H*)-one (**6**) (2 g, 11.5 mmol) in $POCl_3$ (10 mL) was heated to reflux for 2 h. After removal of the solvent, the residue was dissolved in THF (5 mL). A solution of sodium isopropanoxide (11.5 mmol, 1.0 equiv.) in anhydrous 2-propanol (20 mL) was then added dropwise at –20 °C under a N_2 atmosphere. After 1 h, the reaction mixture slowly warmed to room temperature. Concentration and purification with SiO_2 (eluant ethyl ether) afforded compound **7a** as a colorless oil (2.25 g, 90% yield). ^1H NMR (300 MHz, $CDCl_3$): δ = 8.69 (br. s, 2 H, aromatic H), 5.42 [sept, J = 6.3 Hz, 1 H, $(CH_3)_2CHO$], 1.42 [d, J = 6.3 Hz, 6 H, $(CH_3)_2$-CHO] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 164.73, 158.22, 156.44, 90.05, 71.67, 22.14 ppm. MS (ESI): *m*/*z* = 217, 219 [M + H]$^+$. HRMS (ESI): calcd. for $C_7H_{10}{}^{79}BrN_2O$ [M + H]$^+$ 216.9977; found 216.9983.

5-Bromo-2,4-diisopropoxypyrimidine (7b): To a solution of 5-bromo-2,4-dichloropyrimidine (**9**, 2.5 g, 11.5 mmol) in THF (100 mL) was added a solution of sodium isopropanoxide (22 mmol, 2.0 equiv.) in anhydrous 2-propanol (50 mL) dropwise at –20 °C under a N_2 atmosphere. After 1 h, the reaction mixture slowly warmed to room temperature. The routine work-up procedure afforded **7b** as a colorless oil (3.04 g, 96% yield). ^1H NMR (300 MHz, $CDCl_3$): δ = 8.26 (s, 1 H, aromatic H), 5.41 [sept, J = 6.3 Hz, 1 H, $(CH_3)_2CHO$], 5.18 [sept, J = 6.3 Hz, 1 H, $(CH_3)_2$-CHO], 1.40–1.37 [m, 12 H, $(CH_3)_2CHO$] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 166.20, 163.53, 159.38, 98.25, 71.45, 71.29, 22.29, 22.25 ppm. MS (ESI): *m*/*z* = 275, 277 [M + H]$^+$. HRMS (ESI): calcd. for $C_{10}H_{16}{}^{79}BrN_2O_2$ [M + H]$^+$ 275.0395; found 275.0379.

5-Bromo-4-isopropoxy-2-(morpholin-1-yl)pyrimidine (7c): To a solution of 5-bromo-2,4-dichloropyrimidine (**9**, 5 g, 21.9 mmol) in THF (100 mL) was added a solution of sodium isopropanoxide (21.9 mmol, 1.0 equiv.) in anhydrous 2-propanol (50 mL) dropwise at –20 °C under a N_2 atmosphere. After 1h, the reaction mixture slowly warmed to room temperature. Then, morphiline (1.9 g, 21.9 mmol) was slowly added. The reaction mixture was heated at 60 °C for 3 h. Concentration and purification with SiO_2 (eluant diethyl ether) afforded **7c** as a white solid (5.63 g, 85% yield). ^1H NMR (300 MHz, $CDCl_3$): δ = 8.12 (s, 1 H, aromatic H), 5.30 [sept, J = 6.3 Hz, 1 H, $(CH_3)_2CHO$], 3.75–3.72 (m, 8 H, morpholinyl H), 1.38 [d, J = 6.3 Hz, 6 H, $(CH_3)_2CHO$] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 164.58, 160.44, 158.67, 93.27, 70.51, 67.03, 44.84, 22.19 ppm. MS (ESI): *m*/*z* = 302, 304 [M + H]$^+$. $C_{11}H_{16}BrN_3O_2$ (302.17): calcd. C 43.72, H 5.34, N 13.91; found C 44.33, H 5.26, N 13.84. HRMS (ESI): calcd. for $C_{11}H_{17}{}^{79}BrN_3O_2$ [M + H]$^+$ 302.0504; found 302.0493.

5-Bromo-4-isopropoxy-2-(piperidin-1-yl)pyrimidine (7d): By using the same method as for the synthesis of **7c**, compound **7d** was obtained as a colorless oil (6.05 g, 92% yield). ^1H NMR (300 MHz, $CDCl_3$): δ = 8.09 (s, 1 H, aromatic H), 5.30 [sept, J = 6.3 Hz, 1 H, $(CH_3)_2CHO$], 3.72–3.68 (m, 4 H, CH_2NCH_2), 1.64–1.57 (m, 6 H, $CH_2CH_2CH_2$), 1.38 [d, J = 6.3 Hz, 6 H, $(CH_3)_2CHO$] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 164.30, 160.38, 158.73, 91.75, 70.12, 45.50, 26.06, 25.21, 22.21 ppm. MS (ESI): *m*/*z* = 299, 301 [M]$^+$. HRMS (EI): calcd. for $C_{12}H_{18}BrN_3O$ 299.0633, 301.0613; found 299.0634, 301.0617.

5-Bromo-4-isopropoxy-2-(4-tosylpiperazin-1-yl)pyrimidine (7e): By using the same method as for the synthesis of **7c**, compound **7e** was obtained as a white solid (8.29 g, 83% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.04 (s, 1 H, aromatic H), 7.64 (d, J = 8.4 Hz, 2 H, aromatic H), 7.32 (d, J = 8.4 Hz, 2 H, aromatic H), 5.23 [sept, J = 6.3 Hz, 1 H, $(CH_3)_2CHO$], 3.85 (t, J = 4.8 Hz, 4 H, piperazinyl H), 3.02 (t, J = 4.8 Hz, 4 H, piperazinyl H), 2.41 (s, 3 H, CH_3Ph), 1.35 [d, J = 6.3 Hz, 6 H, $(CH_3)_2CHO$] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 164.55, 159.86, 158.74, 144.08, 132.51, 129.97, 127.99, 93.46, 70.55, 46.15, 43.69, 22.13, 21.95 ppm. MS (ESI): m/z = 455, 457 $[M + H]^+$. $C_{18}H_{23}BrN_4O_3S$ (455.37): calcd. C 47.48, H 5.09, N 12.30; found C 47.30, H 5.05, N 12.02.

1,4-Bis(5-bromo-4-isopropoxypyrimidin-2-yl)piperazine (7f): By using the same method as for the synthesis of **7c**, compound **7f** was obtained as a white solid (5.12 g, 91% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.13 (s, 2 H, aromatic H), 5.32 [sept, J = 6.3 Hz, 2 H, $(CH_3)_2CHO$], 3.81 (s, 8 H, piperazinyl H), 1.40 [d, J = 6.3 Hz, 12 H, $(CH_3)_2CHO$] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 164.56, 160.40, 158.79, 93.13, 70.50, 44.15, 22.22 ppm. MS (ESI): m/z = 517 $[M + H]^+$. $C_{18}H_{24}Br_2N_6O_2$ (516.23): calcd. C 41.88, H 4.69, N 16.28; found C 41.83, H 4.68, N 16.11.

4-Isopropoxy-5-vinylpyrimidine (8a): To a solution of **7a** (2.00 g, 9.22 mmol) in a mixture of dioxane (30 mL) and water (6 mL), was added tributyl(vinyl)stannane (4.38 g, 13.82 mmol, 1.5 equiv.), $Pd(dppf)Cl_2$ (337 mg, 0.46 mmol, 0.05 equiv.) and K_2CO_3 (2.55 g, 18.44 mmol, 2 equiv.). After stirring at 60 °C overnight under a N_2 atmosphere, the reaction mixture was filtered through a short pad of silica gel (1 × 5 cm) and washed with ethyl acetate (3 × 50 mL). Removal of the solvent and purification with SiO_2 (eluant 5% ethyl acetate/petroleum ether) afforded **8a** as a colorless oil (1.35 g, 89% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.61 (s, 1 H, aromatic H), 8.47 (s, 1 H, aromatic H), 6.70 (dd, J = 17.7, 11.4 Hz, 1 H, $ArCH=CH_2$), 5.96 (dd, J = 17.7, 1.5 Hz, 1 H, $ArCH=CH_2$), 5.50–5.38 [m, 2 H, $ArCH=CH_2$, $(CH_3)_2CHO$], 1.39 [d, J = 6.0 Hz, 6 H, $(CH_3)_2CHO$] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 167.80, 160.19, 156.97, 154.49, 128.55, 118.55, 70.08, 22.19 ppm. MS (ESI): m/z = 165 $[M + H]^+$. HRMS (ESI): calcd. for $C_9H_{13}N_2O$ $[M + H]^+$ 165.1028; found 165.1030.

2,4-Diisopropoxy-5-vinylpyrimidine (8b): By using the same method as for the synthesis of **8a**, compound **8b** was obtained as a colorless oil (1.36 g, 84% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.24 (s, 1 H, aromatic H), 6.62 (dd, J = 17.7, 11.4 Hz, 1 H, $ArCH=CH_2$), 5.79 (dd, J = 17.7, 1.5 Hz, 1 H, $ArCH=CH_2$), 5.45 [sept, J = 6.3 Hz, 1 H, $(CH_3)_2CHO$], 5.27–5.19 [m, 2 H, $(CH_3)_2CHO$, $ArCH=CH_2$], 1.38 [d, J = 6.0 Hz, 6 H, $(CH_3)_2CHO$], 1.36 [d, J = 6.3 Hz, 6 H, $(CH_3)_2CHO$] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 167.56, 156.52, 128.47, 115.11, 112.83, 100.47, 70.51, 69.98, 22.41, 22.37 ppm. MS (ESI): m/z = 223 $[M + H]^+$. HRMS (ESI): calcd. for $C_{12}H_{19}N_2O_2$ $[M + H]^+$ 223.1447; found 223.1442.

4-Isopropoxy-2-(morpholin-1-yl)-5-vinylpyrimidine (8c): By using the same method as for the synthesis of **8a**, compound **8c** was obtained as a colorless oil (1.31 g, 79% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.15 (s, 1 H, aromatic H), 6.58 (dd, J = 17.7, 11.4 Hz, 1 H, $ArCH=CH_2$), 5.72 (dd, J = 17.7, 1.5 Hz, 1 H, $ArCH=CH_2$), 5.34 [sept, J = 6.3 Hz, 1 H, $(CH_3)_2CHO$], 5.12 (dd, J = 11.4, 1.5 Hz, 1 H, $ArCH=CH_2$), 3.76 (s, 8 H, morpholinyl H), 1.38 [d, J = 6.3 Hz, 6 H, $(CH_3)_2CHO$] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 166.25, 160.66, 156.17, 129.14, 112.84, 108.76, 69.22, 67.15, 44.76, 22.38 ppm. MS (ESI): m/z = 249 $[M]^+$. HRMS (EI): calcd. for $C_{13}H_{19}N_3O_2$ 249.1477; found 249.1480.

4-Isopropoxy-2-(piperidin-1-yl)-5-vinylpyrimidine (8d): By using the same method as for the synthesis of **8a**, compound **8d** was obtained as a colorless oil (1.39 g, 84% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.13 (s, 1 H, aromatic H), 6.57 (dd, J = 17.7, 11.4 Hz, 1 H, $ArCH=CH_2$), 5.68 (dd, J = 17.7, 1.5 Hz, 1 H, $ArCH=CH_2$), 5.34 [sept, J = 6.3 Hz, 1 H, $(CH_3)_2CHO$], 5.07 (dd, J_1 = 11.4, 1.5 Hz, 1 H, $ArCH=CH_2$), 3.77–3.73 (m, 4 H, piperidinyl H), 1.66–1.58 (m, 6 H, piperidinyl H), 1.38 [d, J = 6.3 Hz, 6 H, $(CH_3)_2CHO$] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 166.04, 160.47, 156.25, 129.35, 111.84, 107.50, 68.92, 45.42, 26.22, 25.41, 22.46 ppm. MS (ESI): m/z = 247 $[M]^+$. HRMS (EI): calcd. for $C_{14}H_{21}N_3O$ $[M]^+$ 247.1685; found 247.1687.

4-Isopropoxy-2-(4-tosylpiperazin-1-yl)-5-vinylpyrimidine (8e): By using the same method as for the synthesis of **8a**, compound **8e** was obtained as a white solid (1.51 g, 85% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.07 (s, 1 H, aromatic H), 7.64 (d, J = 8.1 Hz, aromatic H), 7.32 (d, J = 8.1 Hz, aromatic H), 6.53 (dd, J = 17.7, 11.4 Hz, 1 H, $ArCH=CH_2$), 5.68 (dd, J = 17.7, 1.5 Hz, 1 H, $ArCH=CH_2$), 5.28 [sept, J = 6.3 Hz, 1 H, $(CH_3)_2CHO$], 5.10 (dd, J = 11.4, 1.5 Hz, 1 H, $ArCH=CH_2$), 3.89 (t, J = 5.1 Hz, 4 H, piperazinyl H), 3.03 (t, J = 5.1 Hz, 4 H, piperazine H), 2.41 (s, 3 H, $PhCH_3$), 1.34 [d, J = 6.3 Hz, 6 H, $(CH_3)_2CHO$] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 166.24, 159.99, 156.11, 144.04, 132.56, 129.96, 128.92, 128.02, 113.09, 108.90, 69.30, 46.25, 43.59, 22.32, 21.95 ppm. MS (ESI): m/z = 403 $[M + H]^+$. $C_{20}H_{26}N_4O_3S$ (402.51): calcd. C 59.68, H 6.51, N 13.92; found C 59.46, H 6.46, N 13.81.

1,4-Bis(4-isopropoxy-5-vinylpyrimidin-2-yl)piperazine (8f): By using the same method as for the synthesis of **8a**, compound **8f** was obtained as a white solid (0.96 g, 60% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.16 (s, 2 H, aromatic H), 6.58 (dd, J = 17.7, 11.4 Hz, 2 H, $ArCH=CH_2$), 5.72 (dd, J = 17.7, 0.9 Hz, 2 H, $ArCH=CH_2$), 5.37 [sept, J = 6.0 Hz, 2 H, $(CH_3)_2CHO$], 5.12 (dd, J = 11.4, 0.9 Hz, 2 H, $ArCH=CH_2$), 3.87 (s, 8 H, piperazinyl H), 1.40 [d, J = 6.0 Hz, 12 H, $(CH_3)_2CHO$] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 166.26, 160.63, 156.26, 129.18, 112.72, 108.57, 69.21, 44.17, 22.40 ppm. MS (ESI): m/z = 411 $[M + H]^+$. $C_{22}H_{30}N_6O_2 \cdot 1/2H_2O$: calcd. C 62.99, H 7.45, N 20.03; found C 63.27, H 7.31, N 19.47.

[4-O*i*Pr-5-(4,5-dihydroIMES)Cl_2Ru=CH]pyrimidin-2-ylmorpholine (5c): To a solution of **8c** (29 mg, 0.117 mmol), CuCl (35 mg, 0.35 mmol, 3.00 equiv.) in CH_2Cl_2 (10 mL), was added (4,5-DihydroIMES)-$(PCy_3)Cl_2Ru=CHPh$ (**1**, 105 mg, 0.12 mmol, 1.05 equiv.) at 25 °C under a N_2 atmosphere. The reaction mixture was heated to reflux at 40 °C for 1 h. After removal of the solvent, the residue was dissolved in pentane/CH_2Cl_2 (1:1, 2 mL) and filtered through cotton to remove the copper-phosphane precipitate. Further concentration and purification with SiO_2 afforded **5c** as a green solid (58 mg, 69% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 15.86 (s, 1 H, Ru=C*H*Ar), 7.80 (s, 1 H, aromatic CH), 7.05 (s, 4 H, mesityl aromatic CH), 5.40–5.32 [m, 1 H, $(CH_3)_2CHOAr$], 4.17 [s, 4 H, $N(CH_2)_2N$], 3.76–3.67 (m, 8 H, morpholinyl H) 2.46 (s, 12 H, mesityl *o*-CH_3), 2.37 (s, 6 H, mesityl *p*-CH_3), 1.26 [d, J = 6.0 Hz, 6 H, $(CH_3)_2CHOAr$] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 297.06, 211.46, 165.06, 160.20, 149.61, 138.98, 129.90 129.48, 75.98, 66.89, 51.81, 45.22, 21.72, 21.56 ppm. $C_{33}H_{43}Cl_2N_5O_2Ru$ (713.71): calcd. C 55.53, H 6.07, N 9.81; found C 55.23, H 6.08, N 9.59.

[4-O*i*Pr-5-(4,5-dihydroIMES)Cl_2Ru=CH]pyrimidin-2-ylpiperidine (5d): By using the same method as for the synthesis of **5c**, compound **5d** was obtained as a green solid (63 mg, 75% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 15.79 (s, 1 H, Ru=C*H*Ar), 7.77 (s, 1 H, aromatic H), 7.04 (s, 4 H, mesityl aromatic H), 5.40–5.32 [m, 1 H, $(CH_3)_2CHOAr$], 4.17 [s, 4 H, $N(CH_2)_2N$], 3.73 [s, 4 H, piperidinyl $ArN(CH_2)_2$] 2.46 (s, 12 H, mesityl *o*-CH_3), 2.36 (s, 6 H, mesityl *p*-CH_3), 1.65–1.52 [m, 6 H, piperidinyl $(CH_2)_3$], 1.26 [d, J = 6.3 Hz,

6 H, (CH_3)$_2$CHOAr] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 287.68, 212.44, 165.11, 160.22, 149.99, 138.86, 129.42, 128.95, 75.56, 51.78, 46.09, 26.12, 25.12, 22.37, 21.65, 21.49 ppm. $C_{34}H_{45}Cl_2N_5ORu + H_2O$: calcd. C 55.96, H 6.49, N 9.60; found C 55.56, H 6.35, N 9.21.

[4-O*i*Pr-5-(4,5-dihydroIMES)Cl$_2$Ru=CH]pyrimidin-2-yl-4-tosylpiperidine (5e): By using the same method as for the synthesis of **5c**, compound **5e** was obtained as a green solid (75 mg, 74% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 15.91 (s, 1 H, Ru=C*H*Ar), 7.73 (s, 1 H, aromatic H), 7.58 (d, *J* = 8.4 Hz, 2 H, Tosyl Aromatic H), 7.31 (d, *J* = 8.4 Hz, 2 H, Tosyl Aromatic H), 7.03 (s, 4 H, mesityl aromatic H), 5.34–5.26 [m, 1 H, (CH_3)$_2$C*H*OAr], 4.16 [s, 4 H, N(CH_2)$_2$N], 3.92–3.86 [s, 4 H, piperazinyl TsN(CH_2)$_2$], 2.94–2.90 [s, 4 H, piperazinyl ArN(CH_2)$_2$], 2.43 (s, 12 H, mesityl *o*-CH_3), 2.40 (s, 3 H, CH_3PhSO_2N), 2.35 (s, 6 H, mesityl *p*-CH_3), 1.21 [d, *J* = 6.3 Hz, 6 H, (CH_3)$_2$CHOAr] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 296.98, 211.01, 164.99, 160.33, 159.65, 149.42, 144.17, 138.95, 131.84, 129.99, 129.42, 127.87, 127.72, 76.10, 51.75, 45.96, 44.22, 21.99, 21.62, 21.49 ppm. $C_{40}H_{50}Cl_2N_6O_3RuS{\cdot}H_2O$: calcd. C 54.29, H 5.92, N 9.50; found C 54.18, H 5.97, N 9.08.

1,4-Bis[4-O*i*Pr-5-(4,5-dihydroIMES)Cl$_2$Ru=CH]pyrimidin-2-yl-piperazine (5f): By using the same method as for the synthesis of **5c**, compound **5f** was obtained as a green solid (57 mg, 72% yield). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 15.88 (s, 2 H, Ru=C*H*Ar), 7.81 (s, 2 H, aromatic H), 7.05 (s, 8 H, mesityl aromatic H), 5.37 [m, 2 H, (CH_3)$_2$C*H*OAr], 4.17 [s, 8 H, N(CH_2)$_2$N], 3.79 (s, 8 H, piperazinyl CH_2) 2.46 (s, 24 H, mesityl *o*-CH_3), 2.38 (s, 12 H, mesityl *p*-CH_3), 1.26 [d, *J* = 6.3 Hz, 12 H, (CH_3)$_2$CHOAr] ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 297.04, 211.34, 165.04, 160.05, 149.57, 138.96, 129.49, 129.47, 76.05, 51.86, 44.45, 21.71, 21.55 ppm. $C_{62}H_{78}Cl_4N_{10}O_2Ru_2$ (1339.32): calcd. C 55.60, H 5.87, N 10.46; found C 55.41, H 5.98, N 10.32.

General Procedure for RCM and Enyne Metathesis Reaction: To a mixture of alkene (0.1 mmol) in CH_2Cl_2 (50 mL, *c* = 0.02 M) was added a solution of Ru-catalyst (0.1–4 mol-%) in CH_2Cl_2 (1 mL). The resulting mixture was stirred at 0–80 °C for 1–24 h. The solvent was removed under reduced pressure. The crude product was purified by flash chromatography (eluant petroleum ether/ethyl acetate).

1-Tosyl-2,5-dihydro-1*H*-pyrrole (11a):[14] White solid. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.70 (d, *J* = 8.4 Hz, 2 H), 7.30 (d, *J* = 8.4 Hz, 2 H), 5.62 (s, 2 H), 4.09 (s, 4 H), 2.40 (s, 3 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 143.58, 134.21, 129.89, 127.50, 125.56, 55.12, 21.86 ppm. MS (ESI): *m*/*z* = 224 [M + H]$^+$.

1-Tosyl-2,3,6,7-tetrahydro-1*H*-azepine (11d):[15] White solid. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.67 (d, *J* = 8.1 Hz, 2 H), 7.31 (d, *J* = 8.1 Hz, 2 H), 5.76–4.72 (m, 2 H), 3.27 (t, 4 H), 2.42 (s, 3 H), 2.31–2.30 (m, 4 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 143.21, 136.24, 130.32, 129.79, 127.14, 48.53, 30.18, 21.83 ppm. MS (ESI): *m*/*z* = 252 [M + H]$^+$.

Dimethyl Cyclopent-3-ene-1,1-dicarboxylate (11f):[16] Colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 5.61 (s, 2 H), 3.74 (s, 6 H), 3.02 (s, 4 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 172.33, 128.02, 59.08, 53.28, 41.34 ppm. MS (ESI): *m*/*z* = 185 [M + H]$^+$.

2,2-Diphenyl-3-vinyl-2,5-dihydrofuran (11g):[17] Colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.39–7.29 (m, 10 H), 6.30–6.20 (m, 2 H), 5.36 (d, *J* = 17.4 Hz, 1 H), 5.14 (d, *J* = 10.8 Hz, 1 H), 4.81–4.80 (m, 2 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 143.83, 143.50, 129.97, 128.11, 127.67, 125.14, 117.81, 94.83, 73.55 ppm. MS (ESI): *m*/*z* = 249 [M + H]$^+$.

1-Tosyl-1,2,3,6-tetrahydropyridine (11b):[15] White solid. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.65 (d, *J* = 8.1 Hz, 2 H), 7.31 (d, *J* = 8.1 Hz, 2 H), 5.70–5.58 (m, 2 H), 3.54 (d, *J* = 5.4 Hz, 2 H), 3.17 (t, *J* = 5.7 Hz, 2 H), 2.40 (s, 3 H), 2.18–2.17 (m, 2 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 143.63, 133.26, 129.75, 127.77, 125.15, 122.83, 45.07, 42.94, 25.56, 21.85 ppm. MS (ESI): *m*/*z* = 238 [M + H]$^+$.

5-Methyl-1-tosyl-1,2,3,6-tetrahydropyridine (11c):[18] White solid. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.70 (d, *J* = 8.1 Hz, 2 H), 7.34 (d, *J* = 8.1 Hz, 2 H), 5.43 (t, *J* = 1.5 Hz, 2 H), 3.42 (s, 2 H), 3.12 (m, 2 H), 2.42 (s, 3 H), 2.18–2.17 (m, 2 H), 1.65 (s, 3 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 143.76, 133.46, 130.18, 129.93, 127.99, 119.55, 48.60, 42.91, 25.56, 21.96, 21.05 ppm. MS (ESI): *m*/*z* = 252 [M + H]$^+$.

3,4-Dimethyl-1-tosyl-2,5-dihydro-1*H*-pyrrole (11e):[19] White solid. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.73 (d, *J* = 8.4 Hz, 2 H), 7.33 (d, *J* = 8.4 Hz, 2 H), 3.97 (s, 4 H), 2.43 (s, 3 H), 1.54 (s, 6 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 143.34, 134.20, 129.78, 127.55, 126.26, 59.03, 21.85, 11.47 ppm. MS (ESI): *m*/*z* = 252 [M + H]$^+$.

2-Methyl-2-phenyl-3-vinyl-2,5-dihydrofuran (11h):[18] Colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.46–7.44 (m, 2 H), 7.36–7.34 (m, 2 H), 7.31–7.28 (m, 1 H), 6.25 (dd, *J* = 17.7, 0.9 Hz, 1 H), 6.00 (s, 1 H), 5.12–5.02 (m, 2 H), 4.79–4.77 (m, 2 H), 1.81 (s, 3 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 144.87, 144.60, 129.00, 128.43, 127.62, 125.26, 124.48, 117.23, 90.02, 73.42, 24.80 ppm. MS (ESI): *m*/*z* = 187 [M + H]$^+$.

1,1′-Diphenyl-2,2′,5,5′-tetrahydro-1*H*,1′*H*-3,3′-bipyrrole (11i): White solid. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.29 (t, *J* = 7.8 Hz, 4 H), 6.73 (d, *J* = 7.5 Hz, 2 H), 6.61 (d, *J* = 7.8 Hz, 4 H), 5.88 (s, 2 H), 4.33–4.25 (m, 8 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 147.01, 133.51, 129.63, 122.86, 116.36, 111.56, 55.68, 54.83 ppm. MS (ESI): *m*/*z* = 289 [M + H]. HRMS (ESI): calcd. for $C_{20}H_{21}N_2$ [M + H]$^+$ 289.1705; found 289.1702.

General Procedure for CM Reaction: To a mixture of alkene (0.1 mmol) and cross-metathesis partner (0.2 mmol) in CH_2Cl_2 (5 mL) was added a solution of Ru-catalyst (0.5–4.0 mol-%) in CH_2Cl_2 (1 mL). The resulting mixture was stirred at 25 °C for 1–5 h. The solvent was removed under reduced pressure. The crude product was purified by flash chromatography (eluant petroleum ether/ethyl acetate).

Ethyl 7-[(*tert*-butyldimethylsilyl)oxy]hept-2-enoate (13a):[20] Obtained as a colorless oil (*E*/*Z* = 97:3). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 6.95 (dt, *J* = 6.9, 15.6 Hz, 1 H), 5.83 (d, *J* = 15.6 Hz, 1 H), 4.18 (q, *J* = 7.2 Hz, 2 H), 3.60 (t, *J* = 6.0 Hz, 2 H), 2.24–2.17 (m, 2 H), 1.52–1.45 (m, 4 H), 1.27 (t, *J* = 7.2 Hz, 3 H), 0.88 (s, 9 H), 0.03 (s, 6 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 166.87, 149.34, 121.61, 63.10, 60.50, 32.62, 32.37, 26.39, 24.80, 18.80, 14.75, –4.80 ppm. MS (ESI): *m*/*z* = 287 [M + H]$^+$.

7-[(*tert*-Butyldimethylsilyl)oxy]hept-2-enenitrile (13b):[21] Obtained as a colorless oil (*E*/*Z* = 24:77). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 6.72 (dt, *J* = 6.9, 16.2 Hz, 1 H, *E* isomer), 6.48 (dt, *J* = 7.5, 11.1 Hz, 1 H, Z isomer), 5.32 (d, *J* = 11.1 Hz, 1 H), 3.64–3.58 (m, 2 H), 2.47–2.41 (m, 2 H, Z isomer), 2.27–2.21 (m, 2 H, *E* isomer), 1.56–1.50 (m, 4 H), 0.88 (s, 9 H), 0.04 (s, 6 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 155.22, 116.27, 99.89, 62.87, 32.47, 32.04, 26.37, 25.08, 18.79, –4.82 ppm. MS (ESI): *m*/*z* = 240 [M + H]$^+$.

7-[(*tert*-Butyldimethylsilyl)oxy]hept-2-en-1-yl Acetate (13c):[22] Obtained as a colorless oil (*E*/*Z* = 100:0). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 5.81–5.71 (m, 1 H), 5.60–5.51 (m, 1 H), 4.50 (d, *J* = 6.3 Hz, 2 H), 3.59 (t, *J* = 6.3 Hz, 2 H), 2.12–2.05 (m, 2 H), 2.05 (s,

3 H), 1.53–1.39 (m, 4 H), 0.88 (s, 9 H), 0.03 (s, 6 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 172.33, 136.64, 124.10, 65.65, 63.33, 32.69, 32.42, 26.40, 25.55, 21.50, 18.82, –4.78 ppm. MS (ESI): *m*/*z* = 287 $[M + H]^+$.

Methyl 2-{[(Benzyloxy)carbonyl]amino}-8-[(*tert*-butyldimethylsilyl)-oxy]oct-3-enoate (13d): Obtained as a colorless oil (*E*/*Z* = 100:0). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.35–7.30 (m, 5 H), 5.2–5.72 (m, 1 H), 5.50–5.38 (m, 2 H), 5.12 (s, 2 H), 4.85 (t, *J* = 6.3 Hz, 1 H), 3.75 (s, 3 H), 3.59 (t, *J* = 6.0 Hz, 2 H), 2.10–2.03 (m, 2 H), 1.52–1.38 (m, 4 H), 0.89 (s, 9 H), 0.04 (s, 6 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 171.67, 155.60, 136.38, 135.39, 135.22, 128.73, 128.39, 124.17, 67.38, 63.28, 56.03, 52.99, 32.64, 32.32, 26.40, 25.45, 18.81, –4.78 ppm. MS (ESI): *m*/*z* = 436.4 $[M + H]^+$, 458.4 $[M + Na]^+$. HRMS (FT-ICR): calcd. for $C_{23}H_{38}NO_5Si$ 436.2519 $[M + H]^+$; found 436.2512.

***tert*-Butyldimethyl[(6-phenylhex-5-en-1-yl)oxy]silane (13e):**[23] Obtained as a colorless oil (*E*/*Z* = 100:0). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.35–7.16 (m, 5 H), 6.41 (d, *J* = 16.2 Hz, 1 H), 6.27–6.19 (m, 1 H), 3.63 (t, *J* = 6.3 Hz, 2 H), 2.30–2.19 (m, 2 H), 1.57–1.51 (m, 4 H), 0.89 (s, 9 H), 0.05 (s, 6 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 131.15, 130.25, 130.11, 128.69, 127.02, 126.14, 63.45, 33.25, 32.81, 26.43, 26.07, 18.86, –4.73 ppm. MS (ESI): *m*/*z* = 290 $[M]^+$.

3-Phenylallyl Acetate (13f):[24] Obtained as a colorless oil (*E*/*Z* = 100). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.40–7.25 (m, 5 H), 6.68 (d, *J* = 15.9 Hz, 1 H), 6.28 (dt, *J* = 15.9, 6.3 Hz, 1 H), 4.74 (d, *J* = 6.3 Hz, 2 H), 2.10 (s, 3 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 170.98, 136.37, 134.41, 128.82, 128.29, 126.82, 123.36, 65.44, 21.47 ppm. MS (ESI): *m*/*z* = 177 $[M + H]^+$.

ROMP of Norbornene (14):[11] To a solution of norbornene (47.1 mg, 0.5 mmol) in $CDCl_3$ (1 mL) in a flame-dried NMR spectrometry tube, was added Ru catalyst (0.0025 mmol) under an argon atmosphere. After 30 min, the reaction mixture was analyzed by ^{1}H NMR spectroscopy. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 5.34–5.16 (m, 2 H), 2.80–2.70 (m, 1 H), 2.50–2.40 (m, 1 H), 1.80–1.76 (m, 3 H), 1.40–1.30 (m, 2 H), 1.10–1.00 (m, 1 H) ppm.

Supporting Information (see footnote on the first page of this article): General reaction conditions and NMR spectra of all compounds are provided.

Acknowledgments

Support of this work by the grant from National Sciences Foundation of China (20972099), and HRMS and elemental analyses by Prof. Yu-Wu Zhong's group are gratefully acknowledged.

[1] a) T. M. Trnka, R. H. Grubbs, *Acc. Chem. Res.* **2001**, *34*, 18–29; b) K. C. Nicolaou, P. G. Bulger, D. Sarlah, *Angew. Chem.* **2005**, *117*, 4564–4601; *Angew. Chem. Int. Ed.* **2005**, *44*, 4490–4527; c) A. M. Lozano-Vila, S. Monsaert, A. Bajek, F. Verpoort, *Chem. Rev.* **2010**, *110*, 4865–4909; d) T. J. Donohoe, A. J. Orr, M. Bingham, *Angew. Chem.* **2006**, *118*, 2730–2736; *Angew. Chem. Int. Ed.* **2006**, *45*, 2664–2670; e) A. Fürstner, *Angew. Chem. Int. Ed.* **2000**, *39*, 3013; f) R. R. Schrock, A. H. Hoveyda, *Angew. Chem.* **2003**, *115*, 4740–4782; *Angew. Chem. Int. Ed.* **2003**, *42*, 4592–4633.

[2] a) G. C. Vougioukalakis, R. H. Grubbs, *Chem. Rev.* **2010**, *110*, 1746–1787; b) C. Samojłowicz, M. Bieniek, K. Grela, *Chem. Rev.* **2009**, *109*, 3708–3742; c) S. G. Connon, S. Blechert, *Angew. Chem.* **2003**, *115*, 1944–1968; *Angew. Chem. Int. Ed.* **2003**, *42*, 1900–1923; d) G. Lesma, A. Colombo, A. Sacchetti, A. Silvani, *J. Org. Chem.* **2009**, *74*, 590–596; e) A. W. van Zijl, A. J. Minnaard, B. L. Feringa, *J. Org. Chem.* **2008**, *73*, 5651–5653; f) S. Hanessian, H. Sailes, A. Munro, E. Therrien, *J. Org. Chem.* **2003**, *68*, 7219–7233.

[3] a) M. S. Sanford, M. Ulman, R. H. Grubbs, *J. Am. Chem. Soc.* **2001**, *123*, 749–750; b) M. S. Sanford, J. A. Love, R. H. Grubbs, *J. Am. Chem. Soc.* **2001**, *123*, 6543–6554.

[4] a) S. B. Garber, J. S. Kingsbury, B. L. Gray, A. Hoveyda, *J. Am. Chem. Soc.* **2000**, *122*, 8168–8179; b) R. Bujok, M. Bieniek, M. Masnyk, A. Michrowska, A. Sarosiek, H. Stepowska, D. Arlt, K. Grela, *J. Org. Chem.* **2004**, *69*, 6894–6896.

[5] a) V. Thiel, M. Hendann, K. Wannowius, H. Plenio, *J. Am. Chem. Soc.* **2012**, *134*, 1104–1114; b) M. Bieniek, C. Samojzowicz, V. Sashuk, R. Bujok, P. Sledz, N. Lugan, G. Lavigne, D. Arlt, K. Grela, *Organometallics* **2011**, *30*, 4144–4158.

[6] a) H. Wakamatsu, S. Blechert, *Angew. Chem.* **2002**, *114*, 2509–2511; *Angew. Chem. Int. Ed.* **2002**, *41*, 2403–2405; b) H. Wakamatsu, S. Blechert, *Angew. Chem.* **2002**, *114*, 832–834; *Angew. Chem. Int. Ed.* **2002**, *41*, 794–796.

[7] a) K. Grela, S. Harutyunyan, A. Michrowska, *Angew. Chem.* **2002**, *114*, 4210–4212; *Angew. Chem. Int. Ed.* **2002**, *41*, 4038–4040; b) A. Michrowska, R. Bujok, S. Harutyunyan, V. Sashuk, G. Dolgonos, K. Grela, *J. Am. Chem. Soc.* **2004**, *126*, 9318–9325.

[8] a) J. A. Love, J. P. Morgan, T. M. Trnka, R. H. Grubbs, *Angew. Chem.* **2002**, *114*, 4207–4209; *Angew. Chem. Int. Ed.* **2002**, *41*, 4035–4037; b) A. Szadkowska, X. Gstrein, D. Burtscher, K. Jarzembska, K. Wozniak, C. Slugovc, K. Grela, *Organometallics* **2010**, *29*, 117–124.

[9] M. M. Barbasiewicz, M. Bieniek, A. Michrowska, A. Szadkowska, A. Makal, K. Woz′niak, K. Grela, *Adv. Synth. Catal.* **2007**, *349*, 193–203.

[10] During the reaction of **8a** and **8b** with complex **1**, green spots can be observed by TLC monitoring. However, all attempts to isolate these unstable products were unsuccessful.

[11] G. C. Vougioukalakis, R. H. Grubbs, *J. Am. Chem. Soc.* **2008**, *130*, 2234–2245.

[12] The gel permeation (GP) chromatograms and the number average molecular weight (Mn), molecular weight (Mw) and polydispersity index (PDI) data for the polymer products, which were obtained for catalysts **5c, 5d, 5e**, and **5f** are provided in the Supporting Information.

[13] Considering the Grela group's result, we thought that the electro-deficient effect might play a major role in enhancing activity. However, the steric effect might also affect the catalyst's activity, as one referee of this article suggested.

[14] Y. Terada, M. Mitsuhiro, A. Nishida, *Angew. Chem.* **2004**, *116*, 4155–4159; *Angew. Chem. Int. Ed.* **2004**, *43*, 4063–4067.

[15] K. Grela, M. Kim, *Eur. J. Org. Chem.* **2003**, 963–966.

[16] Q. Yao, Y. Zhang, *J. Am. Chem. Soc.* **2004**, *126*, 74–75.

[17] H. Clavier, S. P. Nolan, *Chem. Eur. J.* **2007**, *13*, 8029–8036.

[18] J. Verendel, T. Zhou, J. Q. Li, A. Paptchikhine, O. Lebedev, P. G. Andersson, *J. Am. Chem. Soc.* **2010**, *132*, 8880–8881.

[19] A. Fürstner, O. Guth, A. Düffels, G. Seidel, M. Liebl, B. Gabor, R. Mynott, *Chem. Eur. J.* **2001**, *7*, 4811–4820.

[20] M. E. Jung, J. A. Berliner, L. Koroniak, B. G. Gugiu, A. D. Watson, *Org. Lett.* **2008**, *10*, 4207–4209.

[21] W. E. Crowe, D. R. Goldberg, *J. Am. Chem. Soc.* **1995**, *117*, 5162–5163.

[22] A. Michrowska, R. Bujok, S. Harutyunyan, V. Sashuk, G. Dolgonos, K. Grela, *J. Am. Chem. Soc.* **2004**, *126*, 9318–9325.

[23] G. A. Molander, T. Fumagalli, *J. Org. Chem.* **2006**, *71*, 5743–5747.

[24] L. T. Pilarski, P. G. Janson, K. J. Szabo, *J. Org. Chem.* **2011**, *76*, 1503–1506.

Received: July 25, 2012
Published Online: October 23, 2012

