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Palladium-Catalyzed Trimethylenemethane Cycloaddition of Olefins Activated by the σ -Electron-Withdrawing Trifluoromethyl Group.

Barry M. Trost* and Laurent Debien

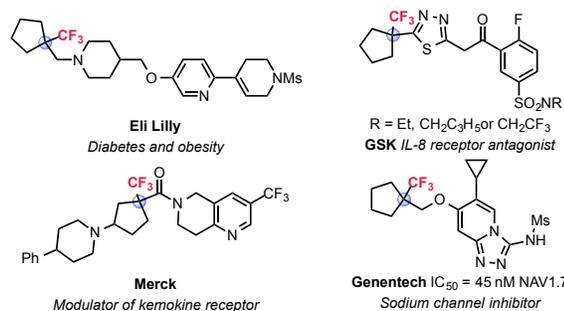
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Supporting Information Placeholder

ABSTRACT: α -Trifluoromethyl-styrenes, trifluoromethylenes and dienes undergo palladium-catalyzed trimethylenemethane cycloadditions under mild reaction conditions. The trifluoromethyl group serves as a unique σ -electron-withdrawing group for the activation of the olefin towards the cycloaddition. This method allows for the formation of exomethylene cyclopentanes bearing a quaternary center substituted by the trifluoromethyl group, compounds of interest for the pharmaceutical, agrochemical and materials industries. In the diene series, the cycloaddition operates in a [3+4] and/or [3+2] manner to give rise to 7- and/or 5 membered rings. This transformation greatly improves the scope of the TMM cycloaddition technology and provides invaluable insights into the reaction mechanism.

Organofluorine compounds are of significant importance for a variety of applications in the pharmaceutical, agrochemical and materials industry.¹ It is indeed well-established that the strategic introduction of fluorine containing functional groups can enhance the physico-chemical properties of organic molecules.² For example, the inclusion of the electron-withdrawing CF_3 group in drug candidates has appeared as a general strategy to increase robustness against metabolic oxidation in the “hit to lead” approach.³ In this context, new methods allowing for the selective introduction of the trifluoromethyl group at positions susceptible to undergo metabolic oxidation will have a significant synthetic utility.

Figure 1. Trifluoromethylated cyclopentanes with biological activity.



Cyclopentanes bearing a quaternary center substituted by the trifluoromethyl group have been found to impart benefits in many bioactive molecules (Figure 1).⁴ However, despite these interesting properties, existing methods for their preparation are extremely limited.⁵

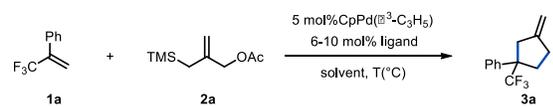
Cycloadditions with trifluoromethyl alkenes are particularly attractive in view of the construction of cyclic compounds bearing CF_3 -quaternary centers. Nevertheless, examples of such cycloadditions where the trifluoromethyl group serves as the activating group are rare and of limited scope. Preliminary work has shown that trifluoropropene can serve as a poorly reactive dienophile.⁶ Bégue and co-workers have also demonstrated one example of a [3+2]-cycloaddition with an azomethine ylide⁷ or a nitron^{8a} and one example of a thermal [4+2]-Diels-Alder reaction with the activated Danishefsky diene.⁸ In contradistinction, to the best of our knowledge, a metal-catalyzed Michael-type cycloaddition exploiting the σ -electron-withdrawing character of the CF_3 group has never been reported.

As part as our long-standing interest in the palladium-catalyzed [3+2]-cycloaddition of trimethylenemethane (TMM) with electron-deficient olefins,⁹ we questioned whether the σ -electron-withdrawing properties of the CF_3 group would be sufficient to activate a trifluoromethyl olefin towards the cycloaddition process. In contrast to previous studies on TMM-cycloadditions, the absence of a strong electron-withdrawing π -acceptor (ketone, ester, nitro, sulfone etc.) capable of decreasing the olefin's LUMO energy level was expected to dramatically challenge the reactivity limits of the TMM-donor. Nevertheless, we recognized that, if reactive, trifluoromethyl alkenes would represent unique mechanistic probes into TMM-cycloadditions. In fact, the mechanism of the TMM-cycloaddition with respect to its concerted nature is still debatable and may strongly depend on the olefinic partner.¹⁰ At the outset of our study, it was thus unclear whether the cycloaddition with trifluoromethyl olefins would give rise to the desired cycloadduct or be interrupted by a fluoride elimination. Indeed, nucleophilic additions to trifluoromethyl alkenes concomitant with fluoride eliminations are well-established processes.¹¹ Herein we report this unprecedented type of transformation in Pd-catalyzed TMM-cycloadditions and strong evidence for a non-concerted pathway.

With hereabove considerations in mind, we began our investigations by examining the reaction of the unsubstituted TMM-donor **2a** with α -trifluoromethylstyrene **1a**. Ligands that proved successful in the TMM-cycloadditions such as triisopropylphosphite or dppe led to poor conversion and no desired product (Table 1, entries 1 and 2). To the extent that the reactivity involves the TMM-complex functioning as a donor interacting with a typical Michael-type alkene acceptor, enhancing the donor properties of the TMM-PdL₂ complex should increase reactivity. While the use of phosphorous triamide did not deliver any of the desired cycloadduct (Table 1, entry 3), phosphoramidite ligands

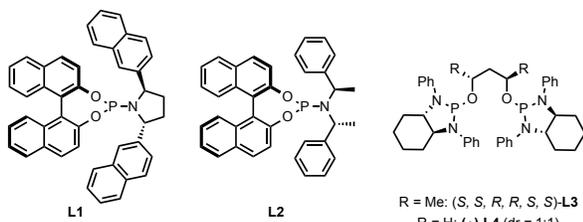
L1 and **L2** gave much more encouraging results (Table 1, entries 4 and 5).¹² Gratifyingly, bidentate diaminophosphite ligand **L3** recently developed in our laboratory,¹³ delivered the targeted cycloadduct **3a** in quantitative GC yield and 75% isolated yield (Table 1, entry 6). The obtention of the desired cycloadduct unaccompanied by fluoride elimination may be suggestive of a concerted mechanism.

Table 1. Selected Optimization Studies.^a



| entry | ligand | solvent | T (°C) | % conv. ^b | % yield ^b |
|-------|-----------------------------------|---------|--------|----------------------|-----------------------|
| 1 | P(O ⁱ Pr) ₃ | dioxane | 60 | 13 | 0 |
| 2 | dppe | dioxane | 60 | 18 | 2 |
| 3 | P(NMe ₂) ₃ | dioxane | 60 | 14 | 0 |
| 4 | L1 | dioxane | 60 | 27 | 6 |
| 5 | L2 | dioxane | 60 | 98 | 66 |
| 6 | L3 | dioxane | 60 | 100 | 100 (75) ^c |
| 7 | L2 | dioxane | 23 | 85 | 46 |
| 8 | L3 | dioxane | 23 | 100 | 100 (79) ^c |
| 9 | L3 | THF | 23 | 100 | 69 ^c |
| 10 | L3 | toluene | 23 | 100 | 91 |
| 11 | L4 | dioxane | 23 | 100 | 100 (80) ^c |

^a All reactions were conducted on a 0.10 mmol scale at 0.33 M for 12 h in the indicated solvent with 1.55 equiv. of **2a**, 5 mol% of PdCp(η^3 -C₃H₅) and 10 mol% of ligand **L1/L2** or 6 mol% of ligand **L3/L4**. ^b Conversions and yields were determined by GC analysis using dodecane as an internal standard. ^c Isolated yield.



Efforts turned to optimizing the reaction variables. Decreasing the reaction temperature showed that diaminophosphite ligand **L3** is best-suited for this system (Table 1, entries 7 and 8). In addition, dioxane was found to be the optimum solvent (Table 1, entries 8, 9 and 10). Finally ligand **L4** was shown to be as effective as the parent enantioenriched ligand **L3** (Table 1, entries 8 and 11). The singular activating role of the trifluoromethyl-group is nicely underlined by the fact that α -methylstyrene **4a** and styrene **4b** are completely inert under the reaction conditions, even when run at 60 °C.

With these optimized conditions in hand, we investigated the scope of the new cycloaddition. A variety of arenes with different steric and electronic constraints were evaluated (Figure 2). Aromatic rings are well tolerated regardless of the position of substitution around the arene ring (**3b-g**). Noteworthy, electron-deficient (**3c,e,f,i,j**), electron-neutral (**3a,b**) and electron-rich (**3d,g,h**) styrenes are all competent substrates in this transformation; a feature that further demonstrates the unique role of the trifluoromethyl group. Interestingly, aryl bromides (**3e**) do not interfere with the cycloaddition process. Other halides such as chlorides (**3f** and **3j**) are also compatible with the mild reaction

conditions. Likewise, heteroaromatic structures of importance in medicinal chemistry such as benzofurans (**3h**) and pyridines (**3i** and **3j**) are well-tolerated. In addition, the reaction allows for the introduction of a variety of useful functional groups such as alkynes (**3g**), acetals (**3g**) and nitriles (**3i**).

Scheme 1. Evidence of the activation by the CF₃-group.

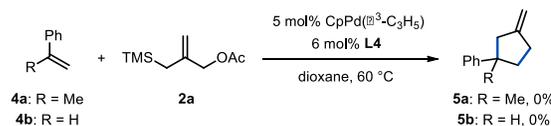
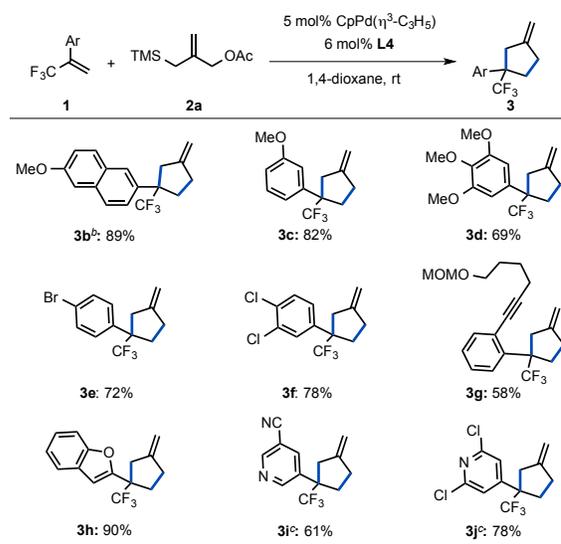


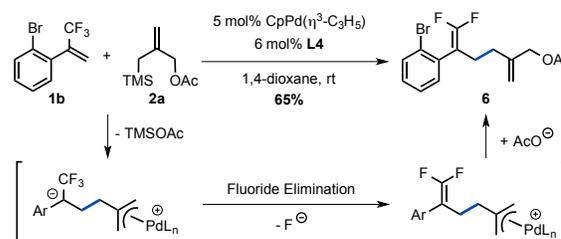
Figure 2. Palladium-Catalyzed [3+2] Reaction with Tri-fluoromethyl styrenes.^a



^a All reactions were performed at 0.33 M concentration with 0.10 mmol of substrate. ^b The reaction was performed on 1 mmol scale. ^c The reaction was performed at 60 °C using 2 equiv. of donor **2a**.

The moderate yield obtained in the case of cycloadduct **3g** may be due to the formation of significant amounts of vinylidene fluoride arising from the undesired elimination of a fluoride anion mentioned earlier as determined by NMR spectroscopy analysis of the crude reaction mixture.¹⁴ Notably, the introduction of a bromide substituent at the ortho- position of the starting styrene **1b** resulted in the exclusive formation of the eliminated product **6** (Scheme 2). In striking contrast to the earlier comment on concertedness, the generation of such an adduct strongly supports the hypothesis of a stepwise mechanism. This observation clearly contrasts with the high yields obtained for substrates lacking substituents at the ortho- position of the arene ring.

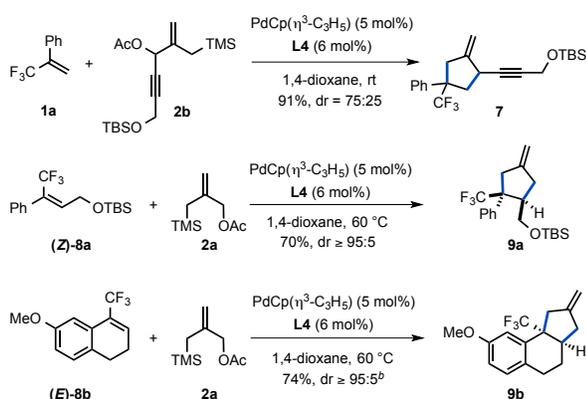
Scheme 2. Competitive fluoride elimination



The generality of the cycloaddition between the standard donor **2** and α -trifluoromethylstyrenes **1** led us to explore even more challenging substrates. Thus, reaction of styrene **1a** with the less reactive TMM-donor **2b** bearing an alkyne substituent stabilizing

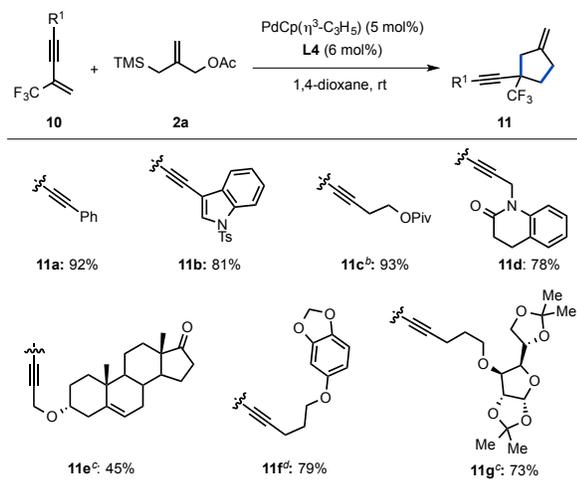
the negative charge in the palladium-TMM complex,¹⁵ gave rise to the corresponding exomethylene cyclopentane **7** in 91% isolated yield (Scheme 3). Gratifyingly, trisubstituted alkene (**Z**)-**8a** delivered cycloadduct **9a** in good yield and as a single diastereoisomer. This transformation constitutes the first example of a cycloaddition involving a trisubstituted trifluoromethylstyrene where activation occurs through the CF₃ group. Indeed, the utility of these substrates was previously limited to the hydrogenation of the trisubstituted alkene.¹⁶ In addition, (*E*)-styrenes are also competent substrates in this transformation as illustrated by the high yielding formation of tricycle **9b** starting from dihydronaphthalene (*E*)-**8b**.

Scheme 3. Extension of the scope of the cycloaddition.^a



^a All reactions were performed at 0.33 M concentration with 0.1 mmol of substrate. ^b The reaction was performed at 0.4 M with 0.3 mmol of substrate.

Figure 3. Cycloaddition with 1,3-enynes.^a



^a All reactions were performed at 0.33 M concentration with 0.10 mmol of substrate **4**. ^b The reaction was performed on 6 mmol scale using 2.5 mol% of PdCp(η³-C₃H₅) and 3 mol% of ligand **L4**. ^c The reaction was performed at 45 °C using 2 equiv. of **2**. ^d The reaction was performed on a 1 mmol scale.

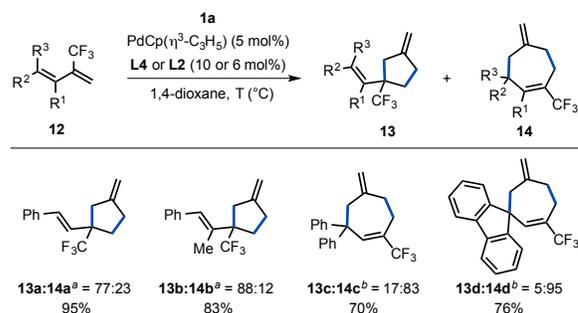
The susceptibility of alkynes to transition metal-catalyzed processes raises the interesting question of chemoselectivity in the use of trifluoromethylenynes. To our delight, 1,3-enynes **10** were found to be particularly effective substrates and the [3+2]-cycloaddition smoothly proceeded (Figure 3).¹⁷ This novel reactivity is exciting since alkynes are very useful building blocks in numerous reactions and especially in metal-catalyzed processes.¹⁸ Aromatic (**11a**), heteroaromatic (**11b**) and even aliphatic R¹ sub-

stituents (**11c-g**) on the alkyne were perfectly tolerated and cyclopentanes **11** were obtained in high yields. Noteworthy, the reaction is compatible with esters (**11c**), amides (**11d**), ketones (**11e**) and masked alcohols (**11g**). In addition, as illustrated by example **11c**, the cycloaddition is efficient on gram scale employing a lower catalyst and ligand loading (Figure 3).

Dienes **12** also successfully reacted. Most interestingly, both [3+2]- and [3+4]-products were obtained in this case (Figure 4). The involvement of both unsaturations in the cycloaddition is noteworthy. In contrast, despite the fact that alkynes are well-known to react in transition metal-catalyzed cycloadditions, enynes only reacted in a [3+2]-fashion. Formation of the [3+2]-cycloadduct is favored by the use of bidentate ligand **L4** (**13a** and **13b**), while Feringa ligand **L2** was found to favor the formation of the [3+4]-cycloadduct (**14c** and **14d**).¹⁹ We previously noted that some dienes may react in both [3+2]- and [3+4]-mode.^{9b} Such competitive behavior seems more consistent with a stepwise mechanism. Indeed, the evidence herein would seem to be best compatible with a short-lived intramolecular ion pair and is working in the same direction as our earlier observation of fluoride elimination (example 3g, Figure 2 and example 6, Scheme 2).

The new reaction allows an easy access to cycloadducts with a unique juxtaposition of functionality. Thus, selective modification of the exo-cyclic double bond is straightforward. In particular, osmium-catalyzed oxidative cleavage readily delivers the corresponding cyclopentanones **15** (Scheme 4, a). A complementary two-step protocol consists in epoxidizing the exo-methylene followed by oxidative cleavage by periodic acid (example **15d**, Scheme 4, b). Interestingly, these seemingly simple ketones are formal products of 1,4-addition of a CF₃ anion onto cyclopentanones and were not previously accessible. Additionally, selective functionalization of the alkyne in cycloadduct **11c** was achieved exploiting our intramolecular ruthenium catalyzed *trans*-hydrosilylation (example **17**, Scheme 4, c). This strategy furnishes cyclic siloxanes, which we previously demonstrated to be useful building blocks for Tamao-Fleming oxidation and Hiyama cross-coupling chemistry.²⁰

Figure 4. [3+2]- versus [3+4]-Cycloadditions with 1,3-dienes



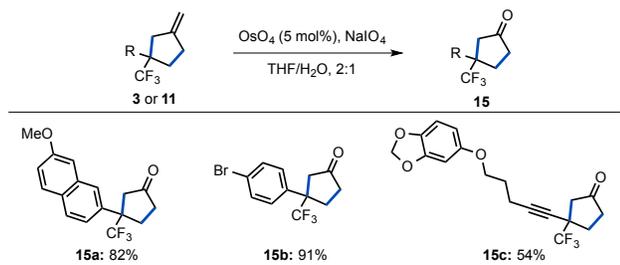
^a The reaction was performed with **L4** at 23 °C. ^b The reaction was performed with **L2** at 60 °C.

In summary, we have demonstrated the first example of the cycloaddition of TMM with olefins activated by a σ -electron withdrawing substituent: the trifluoromethyl group. Diaminophosphite ligand **L4** recently reported in our laboratory was instrumental in the development of this method. The reaction proceeds well with α -styrenes, 1,3-enynes and 1,3-dienes. The availability of the cycloadducts derived from enynes and dienes allow entry to alkyl substituents too. Further investigations into the full scope of this new transformation and towards the development of an enantioselective cycloaddition are ongoing and will be reported in due course. The current results provide good evidence for a stepwise

mechanism albeit with an especially short-lived zwitterion intermediate. The successful development of these transformations allows envisioning the use of new classes of olefins in the TMM cycloaddition beyond the typical Michael-type acceptors.

Scheme 4. Functionalization of the cycloadducts

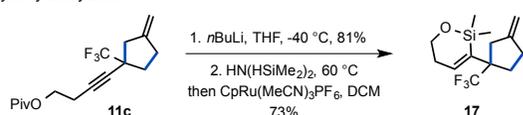
a) Osmium catalyzed selective alkene oxidation



b) Alternative oxidation procedure



c) Alkyne hydrosilylation



ASSOCIATED CONTENT

Supporting Information

Experimental procedures and characterization spectral data. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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REFERENCES

- (1) Banks, R. E.; Smart, B. E.; Tatlow, J. C. eds. *Organofluorine Chemistry, Principles and Commercial Applications*, in *Topics in Applied Chemistry*; Springer Press: New York, 1994.
- (2) (a) Muller, K.; Faeh, C.; Diederich, F. *Science* **2007**, *31*, 1881. (b) Welch, J. T. *Tetrahedron* **1987**, *43*, 3123. (c) Ma, J. A.; Cahard, D. *J. Fluorine Chem.* **2007**, *128*, 975. (d) Meanwell, N. A. *J. Med. Chem.* **2011**, *54*, 2529.
- (3) (a) Filler, R.; Kobayashi, Y.; Yagupolskii, L. M. eds. (1993) *Organofluorine Compounds in Medicinal Chemistry and Biomedical Applications* (Elsevier, Amsterdam). (b) Hagmann, W. K. *J. Med. Chem.* **2008**, *51*, 4359. (b) Nagib, D. A.; MacMillan, D. W. C. *Nature* **2011**, *480*, 224. (d) Barnes-Seeman, D.; Jain, M.; Bell, L.; Ferreira, S.; Cohen, S.; Chen, X.-H.; Amin, J.; Snodgrass, B.; Hatsis, P. *ACS Med. Chem. Lett.* **2013**, *4*, 514.
- (4) (a) Barrett, D. G.; Bueno Melendo, A. B.; Franciskovich, J. B.; Liu, B.; Takeuchi, K. U.S. Patent 8,207,244, June 26, 2012. (b) Adams, G. L.; Brackley, J. A. III; Busch-Petersen, J.; Deng, J.; Fu, W.; Li, H.; Taggart, J. J.; Wang, F.; Wang, Y.; Widdowson, K. L.; Yi, H. U.S. Patent 2010/0298387, November 25, 2010. (c) Butora, G.; Goble, S. D.; Paster-

nak, A.; Yang, L.; Zhou, C.; Moyes, C. R. US Patent 7,598,243, October 6, 2009. (d) Bichler, P.; Chowdhury, S.; Decker, S. M.; Dehnhardt, C. M.; Focken, T.; Grimwood, M. E.; Hemeon, I. W.; Safina, B.; Sheng, T.; Sun, S.; Wilson, M. S.; Zenova, A. Y. Int. Patent WO 2014/153037, September 25, 2014.

(5) The construction of such trifluoromethylated cyclopentanes has essentially relied on the trifluoromethylation of dicarboxylic acid with the hazardous SF_6 : (a) Dmowski, W.; Wolniewicz, A. *J. Fluorine Chem.* **2000**, *102*, 141. See also: (b) O'Connor, M. J.; Boblak, K. N.; Toponka, M. J.; Kindelin, P. J.; Briski, J. M.; Zeng, C.; Klumpp, D. A. *J. Am. Chem. Soc.* **2010**, *132*, 3266.

(6) (a) McBee, E.; Pierce, O. R.; Roberts, C. W. *J. Am. Chem. Soc.* **1955**, *77*, 915. (b) Gaede, B.; Balthazor, T. M. *J. Org. Chem.* **1983**, *48*, 276. (c) Ojima, I.; Yanatabe, M.; Fucikami, T. *J. Org. Chem.* **1982**, *47*, 2051. (d) Tanaka, K.; Mori, T.; Mitsunashi, K. *Bull. Chem. Soc. Jpn.* **1993**, *66*, 263.

(7) For [3+2] cycloadditions, see: Bonnet-Delpon, D.; Bégue, J. P.; Lequeux, T. *Tetrahedron Lett.* **1993**, *34*, 3279.

(8) For thermal [4+2] cycloadditions, and nitrene 1,3-dipolar cycloadditions, see: Bonnet-Delpon, D.; Bégue, J. P.; Lequeux, T.; Ourevitch, M. *Tetrahedron* **1996**, *52*, 59.

(9) For reviews, see: (a) Trost, B. M. *Angew. Chem., Int. Ed.* **1986**, *25*, 1. (b) Chan, D. M. T. Recent Advances in Palladium-Catalyzed Cycloadditions Involving Trimethylenemethane and its Analogs. In *Cycloaddition Reactions in Organic Synthesis*; Kobayashi, S., Jorgensen, K. A., Eds.; Wiley-VCH: Weinheim, Germany, 2002; pp 57–83.

(10) Singleton ^{13}C kinetic isotope effect experiments are suggestive of a stepwise mechanism: (a) Singleton, D. A.; Schulmeier, B. E. *J. Am. Chem. Soc.* **1999**, *121*, 9313 and references cited therein. Our result with stereodefined oxindoles and an enol ether are also supportive of a concerted mechanism: (b) Trost, B. M.; Cramer, N.; Silverman, S. M. *J. Am. Chem. Soc.* **2007**, *127*, 12396. On the other hand, our earlier results with stereodefined α,β -unsaturated esters could be indicative of a stepwise reaction mechanism, see: (c) Trost, B. M.; Miller, M. *J. Am. Chem. Soc.* **1988**, *110*, 3687. (d) Trost, B. M.; Yang, B.; Miller, M. *J. Am. Chem. Soc.* **1989**, *111*, 6482.

(11) α -trifluoromethylstyrenes have been reported to react with nucleophiles to give the corresponding difluoromethylstyrenes. For organolithium reagents additions, see: (a) Bégue, J.-P.; Bonnet-Delpon, D.; Rock, M. H. *Tetrahedron Lett.* **1995**, *36*, 5003. (b) Bégue, J.-P.; Bonnet-Delpon, D.; Rock, M. H. *J. Chem. Soc., Perkin Trans 1* **1996**, 1409. (c) Junji, I.; Hiroyuki, M.; Kotaro, S.; Yukinori, W. *J. Fluorine Chem.* **2004**, *125*, 585. For nitrogen nucleophiles, see: (d) Hamlin, T. A.; Kelly, C. B.; Cywar, R. M.; Leadbeater, N. E. *J. Org. Chem.* **2014**, *79*, 1145. (e) Kohei, F.; Masaki, T.; Junji, I. *Angew. Chem., Int. Ed.* **2012**, *51*, 12059. For reactions with catalytically generated organometallic species, see: (f) Miura, T.; Ito, Y.; Murakami, M. *Chem. Lett.* **2008**, *37*, 10006. (g) Corberan, R.; Mszar, M. W.; Hoveyda, A. H. *Angew. Chem., Int. Ed.* **2011**, *50*, 7079.

(12) For selected examples of phosphoramidites in TMM cycloadditions, see: (a) Trost, B. M.; Silverman, S. M.; Stambuli, J. P. *J. Am. Chem. Soc.* **2011**, *133*, 19483. (b) Trost, B. M.; Bringley, D. A.; Seng, P. S. *Org. Lett.* **2012**, *14*, 234. (c) Trost, B. M.; Maruniak, A. *Angew. Chem. Int. Ed.* **2013**, *52*, 6262. (d) Trost, B. M.; Cramer, N.; Silverman, S. M. *J. Am. Chem. Soc.* **2007**, *129*, 12396.

(13) Trost, B. M.; Lam, T. M. *J. Am. Chem. Soc.* **2012**, *134*, 11319.

(14) A similar competition between the desired cycloaddition and addition-fluoride elimination was observed with α -difluoromethylstyrene. In this case the reaction resulted in the formation of the cycloadduct in 23% isolated yield along with the product of fluoride elimination in 44% isolated yield and as a 1:1 mixture of geometric isomers.

(15) Trost, B. M.; Ehmke, V. *Org. Lett.* **2014**, *16*, 2708.

(16) Engman, M.; Cheruku, P.; Tolstoy, P.; Bergquist, J.; Volker, S. F.; Anderson, P. G. *Adv. Synth. Catal.* **2009**, *351*, 375.

(17) For the Pd-catalyzed [4+2]-benzannulation of 1,3-enynes with alkynes, the presence of the CF_3 group was tolerated but not required for reactivity, see: Zatolochnaya, O. V.; Gevorgyan, V. *Org. Lett.* **2013**, *15*, 2562 and references therein.

(18) Illustrative of this concept are cycloaddition reactions, see: Schore, N. E. *Chem. Rev.* **1988**, *88*, 1081.

(19) Ligand **L2** was identified as a competent ligand for the transformation in the course of the reaction optimization. Reaction with ligand **L4** delivered **13c/14c** in a 33:67 ratio and 82% yield.

(20) For the reactivity of such vinylsiloxanes, see: Trost, B. M.; Ball, Z. T. *J. Am. Chem. Soc.* **2003**, *125*, 30.

